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DTRC–92/001 Improvement of Destroyer Performance Through Optimized Seakeeping Design

Improvement of Destroyer Performance Through Optimized Seakeeping Design

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Optimized hull forms and locations are compared with original configuration to show the potential improvement in performance. This demonstrates that weapon system performance can be improved by a ship design process focused on reducing specific motions.

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NOMENCLATURE

ASW	Anti-Submarine Warfare
CONREP	Connected Underway Replenishment
FAS	Fueling at Sea
GIUK	Greenland - Iceland - United Kingdom
LFE	Lateral Force Estimator
PTL	Percent Time Limited
PTO	Percent Time Operable
SWATH	Small Waterplane Area Twin Hull
UNREP	Underway Replenishment
VERTREP	Vertical Replenishment
VIM	Vibration Isolation Module

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ABSTRACT

This paper will describe the effect of system location and hull form optimization on a destroyer class ship for three missions. The three missions considered are towed array deployment, gun fire, and underway replenishment. They are all typical destroyer missions; yet, the motion requirements are all different. The towed array deployment mission requires low relative motion at the stern; gun fire requires low absolute motions; and underway replenishment has more human factor considerations than the other two. The mission performance will be evaluated by use of criteria sets and percent time operabilities.

Optimized hull forms and locations are compared with the original configuration to show the potential improvement in performance. This demonstrates that weapon system performance can be improved by a ship design process focused on reducing specific motions.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

A weapon system's performance is dependent upon the motions of the platform carrying it. Severe motions, in addition to degrading human performance, can impair sensor capability, reduce gun fire accuracy, and may even prevent missile launching. With this in mind, providing motion levels such that system performance is not significantly degraded in higher sea states is necessary. The motions of a given system can be reduced by relocating the system, optimizing the hull form for improved mission performance and/or adding motion stabilization systems.

The current trend in ship board systems is to individually motion stabilize sensitive systems. This results in bigger, heavier systems. By designing the ship for reduced motion characteristics and placing the system at advantageous locations, it is possible to reduce the amount of individual motion stabilization required. Reducing platform motions also improves crew performance and reduces downtime due to lack of maintenance.

The most prevalent design philosophy for reduced motions is to design the hull for reduced heave and pitch, and then use appendages and roll stabilizers to reduce roll. Various seakeeping optimization programs are available that follow this methodology. The program, SKOPT,[1] performs constrained optimization to reduce vertical motion subject to geometric and motion limits for head seas at one ship speed. The limiting motions are slamming, pitch, and acceleration at the bow and midships. However, it is possible to use other limiting motions, such as relative motion or vertical velocity, in the optimization process.

As a starting point, a destroyer size ship was chosen as the platform for three missions: towed array deployment, gun fire, and underway replenishment. See Fig. 1 for the body plan of the baseline hull form. These are typical destroyer missions and each has its own limiting motions. The baseline ship is evaluated for each of these missions in terms of criteria sets and percent time operabilities (PTOs). An optimum hull form for each mission is generated by optimizing to reduce the limiting motions from the criteria sets. The same type of appendages are added to the optimum hulls as on the baseline to reduce roll. The baseline and optimal hulls results are compared.

OPTIMIZATION METHODOLOGY

The optimization program, SKOPT,[1] uses an exponential random search over ship parameters and coefficients to find an optimum hull form. The search is constrained by geometric limits. The optimized motions can include slamming, pitch, vertical acceleration at the bow and midships, relative motion, and vertical velocity. The optimization function can combine both resistance and seakeeping results to design a compromise ship. For this study the hull forms were optimized without regard for resistance. The method used to predict seakeeping is a simple vertical plane, head seas only prediction. The added mass and damping are calculated using Lewis forms.

The optimization process usually improves seakeeping performance by making the heave, pitch, and roll natural periods shorter. As a result, there is a typical optimized seakeeping hull form with respect to the range of ship parameters and coefficients. Generally these ships are as long and wide as possible, with draft being on the low end of the range. The displacement is typically very close to the maximum allowed. The waterplanes are very full, with the aft being very wide all the way to the transom. The volume is moved forward. These waterplane and volume distributions produce wide V shaped sections forward and flat shallow sections aft. Using stern slamming as a seakeeping criteria for optimizing would probably make the sterns deeper.

Optimized hull forms for the different missions were generated. The parameter ranges were ±20% of the baseline hull form values and the limiting motions depended on the mission examined. The towed array deployment and underway replenishment (UNREP) missions were optimized at 10 knots, and the gun fire mission at 20 knots. The resulting optimized hull forms were all different, but had the same basic shape. The roll periods of the optimized hull forms were made approximately equal to that of the baseline. See Table 1 for a comparison of the hull form optimization results and the baseline ship.

OPERABILITY METHODOLOGY

The seakeeping qualities of a ship can be conveniently predicted using modern strip theory motion programs, such as the Standard Ship Motion Program (SMP84).[2, 3] The PTOs are calculated using the ship transfer functions to predict motion responses as a function of speed, heading, and joint probability of significant wave heights and modal periods. PTO calculations allow a relative comparison of ships at specific geographic locations for a given mission. PTOs for the different missions at the GIUK gap* and a representative open ocean North Atlantic point† were calculated using the Seakeeping Evaluation Program (SEP).[4]

The seaway is modeled by environmental data supplied by the Spectral Ocean Wave Model (SOWM) data base. The SOWM data base contains archived wind data used by the Fleet Numerical Oceanography Center (FNOC) to hindcast wave fields for approximately 1500 locations throughout the northern hemisphere. Each ship response is

*61.1°N; 14.6°W.
†55.9°N; 26.7°W.

compared to the limiting criteria in each of the wave spectra, characterized by a significant wave height and modal period, which might be encountered in the geographic location of interest. The probabilities of occurrence of the spectra for which none of the motion limits are exceeded are summed to calculate the PTO. The probability of failure is calculated by summing the probabilities of occurrence for each failing wave height-modal period combination. PTOs were calculated using winter season wave data to represent the most severe season in the northern Atlantic Ocean.

Furthermore, the PTOs represent statistical values and should be treated accordingly. This means a PTO of 80%, represents 80% operability during a 20 year period. It does not necessarily mean that for any five day period, a ship can successfully operate during four of those five days.

TOWED ARRAY DEPLOYMENT

Anti-submarine warfare is becoming more and more important due to the increasing submarine threat. The combination of hull mounted sonar, ASW helicopters, and towed arrays is the surface ship response to this threat. The performance of all these systems is degraded by excessive ship motions.

Towed sonar arrays are subject to both performance and deployment degradation due to ship motions. The amount of motion transferred to the array depends upon ship speed, array length, and depth. The array equipment is designed to operate in high sea states. At zero and low speeds, the array hangs nearly vertically in the water and ship motion is easily transferred to the array. When ship speed increases, the array begins to stream out behind the ship and less ship motion is transferred. Arrays by their very nature do not respond to the high frequency excitation caused by ship motions. Also arrays are equipped with a Vibration Isolation Module (VIM) to prevent the array being affected by ship motion. So in effect, the only ship motion that affects array performance is maneuvering. In that light, the criteria chosen reflect deployment limits.

Relative motion between the tow point and water surface is important when deploying any sort of body over the side of the ship. Model tests of SWATHs deploying and retrieving towed arrays also indicated that relative motion of the tow point was important.

The actual limiting value used is 80% of the average of the tow point relative motion of two destroyers and two frigates in NATO Sea State 6 at the worst heading and 15 knots. The tow point was located at station 19.75, along the centerline, and on the main deck. These values have some basis in reality and are somewhat conservative. The relative motion criterion was combined with standard mobility mission criteria. The criteria used were:

Roll	8° significant single amplitude	
Pitch	3° significant single amplitude	
Slams	20/hour	station 3
Wetness	30/hour	station 0
Abs. Vert. Accel.	0.3 g significant single amplitude	tow point
Lateral Force Estimator*	0.14 g significant single amplitude	tow point
Relative Motion	2.3 m significant single amplitude	tow point.

The value for absolute vertical acceleration is less than the generally accepted 0.4 g's due to recent trials experience.

BASELINE RESULTS

The most limiting motion is roll, having limiting significant wave heights of one third to one half that of other limiting motions; see Table 2. Roll limitation predominates at headings between bow and stern quartering. Relative motion appeared where pitch usually limits operability, i.e., at head and following seas. Pitch is a limiting motion in a transition region between relative motion and vertical acceleration limitations. Neither slamming nor deck wetness is a limiting criterion. The vertical acceleration limit at the tow point is a habitability limit for crew working in that area and limits operability before slamming and wetness.

To improve total operability it would seem reasonable to reduce roll instead of relative motion and vertical acceleration of the tow point. This would improve those

*Lateral Force Estimator is an approximation to the ship referenced transverse acceleration based on frigate flight deck evolutions. The assumptions used for its derivation may not be valid over the entire ship or for certain ship sizes.

speed-heading combinations that were limited by roll and leave the others unaffected. While increasing PTO, this approach does not improve the situation at the tow point. Also towed array deployment is usually conducted in head or following seas. Reducing vertical motions would improve that regime, i.e., head and following seas, and would also increase operability.

The optimization process should reduce vertical motion, increasing operability in head and following seas.

OPTIMIZATION RESULTS

The optimization was carried out for a speed of 10 knots. The hull form has wide V cross sections forward to accommodate the large waterplane. The aft sections are very wide and shallow; see Fig. 2. Optimization was tried at higher speeds, but the results were better only at higher speeds and actually worse at reasonable mission speeds.

The analysis of this mission requires careful attention due to the number of criteria involved. The total PTO for the optimized ship was 17 percentage points better than the baseline ship, indicating the optimization process was working. The improvements that led to the increase did not come from reducing the percent time limited (PTL) by pitch and relative motion, but rather roll; see Table 3. As the optimization process ignores lateral motions, this would seem to indicate the optimization process is not working, but such is not the case. The confusion arises from considering all speed-heading combinations equally and motion interaction when calculating PTO. If all motions are reduced an equal percentage, the PTO will increase and the all the PTL by individual criterion will decrease an equal percentage. However, if the motions are reduced unequally, the PTO will increase, but the PTL of individual criterion will not maintain their previous ratios. Such is the case here.

The improvement in roll performance is much more than the improvement in relative motion. This means that speed-heading combinations previously limited by roll are being limited by another criterion for the optimized ship. That is why even though the relative motion of the tow point is being reduced, the percent time limited by relative motion increases after optimization. Stated another way, the limiting wave height for relative motion has been increased, but the limiting wave height for roll has been increased even more.

Examining only the speeds and headings that are limited by relative motion for the baseline and optimized ships reveals the effect of optimizing. For the condition optimized , head seas at 10 knots, the PTO increased about 10 percentage points. The optimized hull form shows an improvement at speeds less than 20 knots for every heading limited by relative motion. At speeds of 20 knots and above, relative motion limits operability in stern seas headings where the optimized ship is somewhat worse than the baseline ship. See Table 4 for the optimized towed array hull PTO by speed-heading combinations.

GUN FIRE MISSION

Ship motions affect missiles and deck guns differently. Severe motions affect missile availability and deck gun accuracy. Some missiles' internal programming may prevent launching at certain roll and pitch angles. Canister reloading becomes difficult if ship motions are too great. Deck guns are easily reloaded and can be fired in virtually any sea conditions, though actually hitting the target is questionable in heavy seas.

The criteria set used for the gun fire mission is a combination of standard habitability criteria and gun motion limits. The most important motion has been found to be the absolute vertical velocity. Accuracy was found to be seriously degraded when the significant absolute vertical velocity of the gun mount[5] was greater than 0.9 m/s. The gun was placed at three different stations, 3.3, 12.5, and 18.5, to determine the effect of location on operability. The criteria used were:

Roll	8° significant single amplitude	
Pitch	3° significant single amplitude	
Slams	20/hour	station 3
Wetness	30/hour	station 0
Abs. Vert. Velocity	0.9 m/s significant single amplitude	gun mount.

BASELINE HULL RESULTS

The operabilities for the gun fire mission were surprisingly low. Vertical velocity is by far the most limiting motion, about four times as limiting as roll. The limiting wave height and associated operabilities are very low for head to beam seas, but are much larger for heading aft of beam seas. In fact, it is only for headings aft of beam seas that other criteria limit operability. Roll limits operability for stern quartering seas at all speeds; pitch is the limiting motion for following seas at high speeds; see Table 5. These are regions where the encounter frequency is usually very small. As a result the response becomes slower and the velocity limit is no longer being exceeded.

The best way to reduce velocity of the gun mount is through tuning stabilization, i.e., moving the response natural frequency away from the seaway spectral peak. The vertical motion can be decreased by either making the ship response stiffer or softer. To reduce velocity, the vertical motion should be decreased and the natural period increased. From the SEP results, it would seem that a soft ship, rather than a stiff ship, moves the natural period in the correct direction. This description of the required platform brings to mind a SWATH with it's long natural heave and pitch periods.

So from this respect we do not expect much from the optimization procedure. The ships' periods naturally fall near the seaway energy and SKOPT has to work overtime to reduce the motion faster than the natural frequency increases.

OPTIMIZED HULL RESULTS

The optimized hull form had a smaller displacement than the baseline ship, but was longer. The draft and beam were slightly smaller than the baseline. The sections were wide V sections forward and wide, shallow sections aft; see Fig. 3. The mission operability was limited by absolute vertical velocity, roll, and pitch, with vertical velocity dominating roll and pitch. Vertical velocity was the limiting criterion for all speed–heading combinations forward of beam seas and about half the combinations aft of beam seas. The optimized ship had a 7 to 8 percentage point improvement for station 3.3 and 18.5 locations. The improvement at station 12 is about 18 percentage points. The break down of PTL by each criterion reveals most of this improvement comes from roll. This is not to say vertical velocity and pitch were not reduced, but rather roll is reduced more than vertical velocity or pitch. The optimization process did in fact work as the limiting significant wave height increased at every speed–heading combination for the optimized ship. See Table 6 for comparison of PTO results from optimization.

The PTOs follow the same trend as absolute vertical velocity, which is reasonable considering that vertical velocity is the most limiting criterion. This shows that the most advantageous gun location is at station 12.5, and significant improvement can be made by simply considering motions when doing arrangements. This location does require conscientious arrangements to maintain reasonable fields of fire, but ships with midships guns do exist.

UNDERWAY REPLENISHMENT

The three methods of Underway Replenishment (UNREP) are: Connected Replenishment (CONREP), Vertical Replenishment (VERTREP), and Fueling at Sea (FAS). During CONREP and FAS, the ships are physically connected, and stores and fuel are passed from ship to ship. Helicopters transport palletized stores from ship to ship during VERTREP operations.

Severe ship motions degrade UNREP operations by making course keeping and pallet control difficult. The winches, cables, and hydraulic ram tensioners used during UNREP are designed to withstand high sea states and will operate effectively as long as the ships maintain the proper separation. Heavy seas make this difficult and prevent hook ups. These ship to ship interactions and maneuvering problems are beyond the scope of standard frequency domain analysis. Therefore, this operability assessment ignores degradations due to ship handling.

The limitations due to pallet control and habitability requirements are readily investigated using frequency domain techniques. These limits are combined to form the criteria used in operability assessment. The criteria set used was the following generic UNREP set:

Roll	5° significant single amplitude	
Pitch	2° significant single amplitude	
Slams	20/hour	station 3
Wetness	30/hour	station 0
Abs. Vert. Accel.	0.3 g significant single amplitude	connect point
Lateral Force Estimator	0.14 g significant single amplitude	connect point.

The vertical acceleration and Lateral Force Estimator (LFE) are calculated at stations 5, 10, and 15 to determine location dependence.

BASELINE RESULTS

Roll limits operability at all speeds for beam to stern quartering seas and low speed for bow quartering to beam seas. Pitch limits operability at all other speed-heading combinations. See Table 7 for limiting motions and PTO by speed and heading.

There is not much difference in the PTO's with respect to speed because ship motions are such that they exceed the limits almost equally at all speeds.

There is a large difference with respect to heading angle, with the lowest operabilities occurring for the headings predominantly limited by roll. The operabilities drop with increasing speed. The operabilities for pitch decrease with increasing speed for headings forward of beam seas and increase with speed for headings aft of beam seas.

When the UNREP station is at station 5, acceleration limits begin to come into play. They appear at headings between bow quartering and beam seas and at the higher speeds. Lateral Force Estimator appears only at beam seas and seems to be modal period dependent because different speeds are limited at different geographic points. For UNREP at stations 10 and 15, roll and pitch are the only limiting motions.

The PTOs are virtually the same for all the UNREP stations, not because motions are the same, but rather the predominant limiting motions, roll and pitch, are location independent. So no matter where the UNREP station is located, roll and pitch have the same values resulting in similar PTOs.

OPTIMIZED HULL RESULTS

The optimized ship, shown in Fig. 4, had marked reductions in both pitch and roll. The percent time limited by roll decreased about 12 percentage points; and that of pitch decreased about 6 percentage points. This is in contrast to the other optimized hulls that experience percent time roll limitation decreases and percent time pitch limitation increase: see Table 8.

The one criteria that became more restrictive was Lateral Force Estimator, which increased 1.5 percentage points in the optimized ships. All of the limiting wave heights are higher for the optimized ship than the baseline ship. This increase in LFE failure is a result of behavior similar to roll for the Towed Array Deployment mission.

Both UNREP and Towed Array Deployment missions have large reductions in roll PTL. These improvements are due to two effects: increased hull damping and appendages. The effect of tuning stabilization is negligible as all the roll periods are approximately equal. To examine the effect of appendages on the operability results, bare hull comparisons between the baseline and the UNREP optimized hull were made. The difference between the bare hull PTOs was about six percentage points. Most of this difference comes from a reduction in pitch, rather than roll. This indicates that the optimized hull form has only slightly higher roll damping, and almost all of the roll improvement derives from the appendages; see Table 9. The main appendages in question are the bilge keels, which are placed higher on the optimized hull than the baseline hull. So most of the roll improvement of the optimized ships is not due to the hull form, but rather to more advantageous appendage location.

OPTIMIZED HULL COMPARISON

The hull forms selected by the optimization program for the different missions were very similar, except for the small displacement gun fire ship. To ensure the program was actually optimizing the hull to reduce the desired motions and the improved results were not the result simply reducing pitch, each hull was run for the other missions. See Table 10 for the average PTO of the cross runs.

The first item to note is that the optimized ships are always better than the baseline ship, even for the missions they were not optimized for. Second, there is not much of a spread in the optimized results. This is to be expected because the hull shapes were similar.

The towed array mission PTOs for the optimized ships were all close to each other. The towed array and gun fire ships actually being equal. The gun fire ship had the highest PTO for the gun fire mission, being marginally better than the UNREP ship, which looked like a large gun fire ship. The gun fire ship also out performs the UNREP ship at the UNREP mission.

This indicates that the vertical velocity limit used when optimizing is slightly more stringent than the UNREP pitch limit, forcing the hull to be better. Other motions of interest, i.e., pitch, vertical acceleration, and relative motion, are reduced at the same time. Therefore, a ship designed to perform all three missions would be the gun fire mission ship, which is the somewhat unexpected long and small choice. This is due to the vertical velocity limit being much stricter than any of the others used by SKOPT.

CONCLUSIONS

A baseline destroyer class ship was compared with three hull forms that had been specifically optimized with respect to three different missions. The missions were: towed array deployment, gun fire, and underway replenishment. The comparisons were made using Percent Time Operable as a measurement. The optimized ship was better than the baseline ship in every instance. Also the optimized hull forms were not all exactly the same, e.g., the gun fire mission being smaller. This demonstrates that a unique optimum ship exists and it is possible to optimize a ship to perform a specific mission once the limiting motions are known.

The choice of which limiting motion to optimize the hull for is important as demonstrated by the gun fire ship which out performed the others, although only optimized for absolute vertical velocity. The optimized hull form in itself reduces heave and pitch, but also allows for advantageous appendage location and sizing to reduce roll.

While focusing a design exclusively on seakeeping is not recommended, considering seakeeping aspects early in the design is. The improvements in operability are large and worth taking advantage of whatever the mission or the limiting motion.

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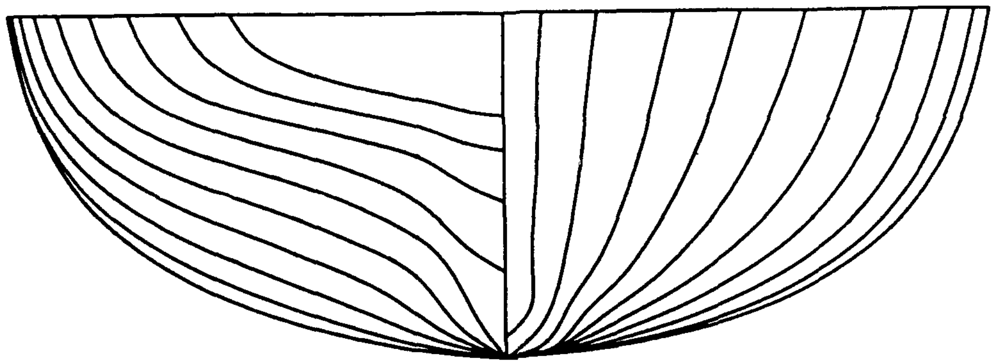

Fig. 1. Body plan of baseline hull form.

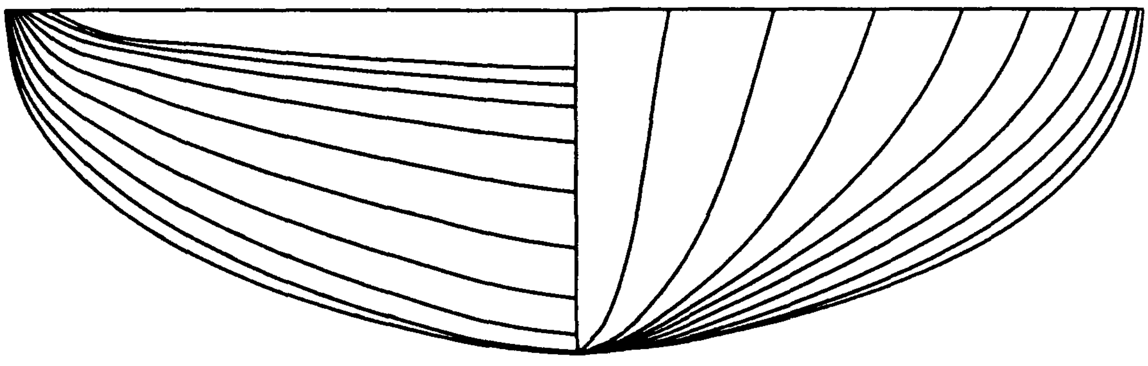

Fig. 2. Body plan of optimized Towed Array hull form.

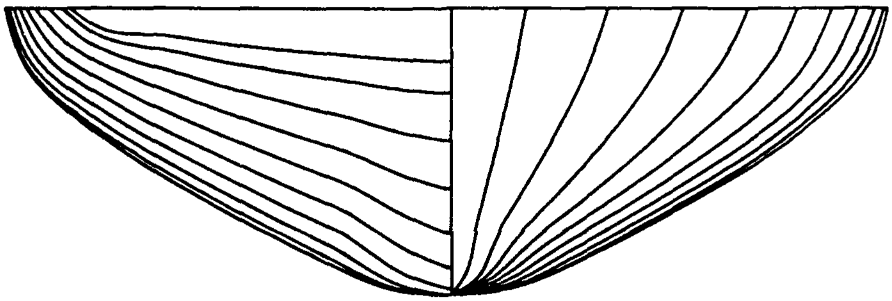

Fig. 3. Body plan of optimized Gun Fire hull form.

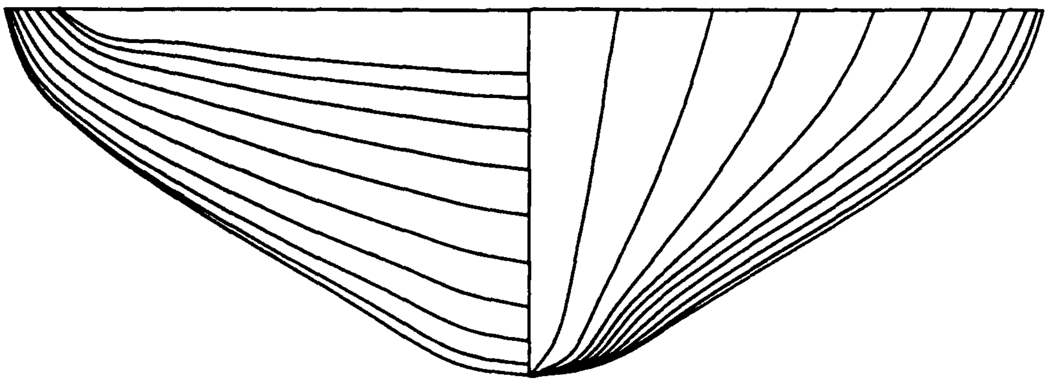

Fig. 4. Body plan of optimized UNREP hull form.

Table 1. Comparison of hull form parameters for baseline and optimized hull forms.

(a) Principle dimensions and form coefficients.

	Baseline	Gun Fire	UNREP	Array
LBP	154.2	179.2	179.2	158.6
B	15.61	14.14	16.52	18.13
T	5.75	4.63	5.93	5.56
Δ	6,179	5,398	7,564	7,600
C_b	0.493	0.449	0.420	0.464
C_p	0.609	0.661	0.647	0.603
C_{vp}	0.652	0.549	0.510	0.558
C_m	0.809	0.678	0.649	0.769
C_{wp}	0.724	0.818	0.824	0.831
C_{wpf}	0.566	0.679	0.679	0.679
C_{wpa}	0.882	0.957	0.970	0.984
C_{vpf}	0.734	0.635	0.595	0.696
C_{vpa}	0.571	0.488	0.450	0.463

(b) Roll motion parameters.

KM	7.75	11.44	10.30	8.55
KG	6.41	9.63	8.65	7.06
GM	1.34	1.80	1.65	1.49
T_ϕ	11.27	11.84	11.52	11.46
BKS[1]	0.76	0.76	0.76	0.76
BKL[2]	46.30	59.58	59.74	54.7

[1] Bilge keel span.
[2] Bilge keel length.

Table 2. Limiting criteria and longcrested PTO by speed and heading of Towed Array Deployment mission for the baseline hull form at GIUK Gap.

(a) Limiting criteria.

Speed	Ship Heading Angle (deg)												
	Head						Beam						Following
(kn)	180	165	150	135	120	105	90	75	60	45	30	15	0
0	RM	RM	R	R	R	R	R	R	R	R	RM	RM	RM
5	RM	RM	RM	R	R	R	R	R	R	R	R	RM	RM
10	RM	RM	RM	R	R	R	R	R	R	R	RM	RM	RM
15	RM	RM	P	R	R	R	R	R	R	RM	RM	RM	RM
20	P	P	A	A	A	R	R	R	R	RM	RM	RM	RM
25	A	A	A	A	A	A	R	R	R	RM	RM	RM	RM
30	A	A	A	A	A	A	R	R	R	RM	RM	RM	RM

P = Pitch; R = Roll; RM = Relative Motion
A = Vertical Acceleration.

(b) Percent time operable.

Speed	Ship Heading Angle (deg)												
	Head						Beam						Following
(kn)	180	165	150	135	120	105	90	75	60	45	30	15	0
0	58	59	44	27	22	22	23	21	22	27	45	55	54
5	62	63	58	38	30	28	27	23	21	28	62	65	63
10	65	66	69	51	38	33	30	23	19	42	76	70	68
15	65	66	66	61	48	40	33	22	20	91	80	73	71
20	61	62	63	63	54	46	37	21	54	93	81	72	70
25	55	55	55	56	54	51	41	19	81	94	78	68	65
30	44	44	44	45	49	53	44	16	95	93	73	63	60

Average percent time operable = 51 percent.

Table 3. Towed Array Deployment longcrested percent time limited by various motions.

GIUK Gap	Baseline	Optimized
Roll	30	17
Pitch	5	3
Wetness	0	0
Slams	0	0
Vert. Accel.	4	1
Rel. Motion	7	8
LFE	1	1
Total PTO	52	69

Open North Atlantic	Baseline	Optimized
Roll	35	22
Pitch	7	6
Wetness	0	0
Slams	0	0
Vert. Accel.	5	1
Rel. Motion	9	10
LFE	1	1
Total PTO	42	59

Table 4. Limiting criteria and longcrested PTO by speed and heading for optimized Towed Array Deployment hull form at GIUK Gap.

(a) Limiting criteria.

Speed	Ship Heading Angle (deg)												
	Head						Beam						Following
(kn)	180	165	150	135	120	105	90	75	60	45	30	15	0
0	RM	RM	R	R	R	R	R	R	R	RM	RM	RM	RM
5	RM	RM	RM	RM	R	R	R	R	R	R	RM	RM	RM
10	RM	RM	RM	RM	R	LFE	R	R	R	R	RM	RM	RM
15	RM	RM	RM	P	LFE	LFE	R	R	R	R	RM	RM	RM
20	RM	RM	S	S	A	LFE	R	R	R	RM	RM	RM	RM
25	S	S	S	S	A	A	R	R	R	RM	RM	RM	RM
30	S	S	A	A	A	A	LFE	R	R	RM	RM	RM	RM

P = Pitch; R = Roll; RM = Relative Motion; S = Slams;
A = Vertical Acceleration; LFE = Lateral Force Estimator.

(b) Percent time operable.

Speed	Ship Heading Angle (deg)												
	Head						Beam						Following
(kn)	180	165	150	135	120	105	90	75	60	45	30	15	0
0	61	63	66	52	44	49	57	48	44	52	66	63	61
5	69	70	74	70	61	62	67	51	44	56	76	71	70
10	76	77	80	82	75	73	75	52	43	64	83	77	75
15	79	79	80	82	83	79	80	51	40	71	85	78	76
20	78	78	79	81	87	84	84	48	36	93	83	74	72
25	75	75	78	80	86	86	86	43	53	94	75	66	63
30	71	72	72	73	78	88	88	36	72	86	64	56	54

Average percent time operable = 69 percent.

Table 5. Limiting criteria and longcrested PTO by speed and heading for optimized Gun Fire Mission hull form at GIUK Gap, station 3.3.

(a) Limiting criteria.

Speed	Ship Heading Angle (deg)												
	Head						Beam						Following
(kn)	180	165	150	135	120	105	90	75	60	45	30	15	0
0	V	V	V	V	V	V	V	V	V	V	V	V	V
5	V	V	V	V	V	V	V	V	V	V	V	V	V
10	V	V	V	V	V	V	V	V	V	V	V	V	V
15	V	V	V	V	V	V	V	V	R	V	V	V	V
20	V	V	V	V	V	V	V	V	R	V	V	V	V
25	V	V	V	V	V	V	V	R	R	V	V	P	P
30	V	V	V	V	V	V	V	R	R	V	P	P	P

P = Pitch; R = Roll; V = Vertical Velocity.

(b) Percent time operable.

Speed	Ship Heading Angle (deg)												
	Head						Beam						Following
(kn)	180	165	150	135	120	105	90	75	60	45	30	15	0
0	45	44	39	32	25	19	24	23	30	38	45	50	51
5	34	33	29	25	20	16	24	26	35	46	55	50	62
10	26	25	23	19	15	14	24	28	42	56	67	73	75
15	20	20	18	15	12	12	24	32	49	68	78	83	85
20	16	16	14	12	10	10	24	36	54	79	88	92	93
25	13	13	11	9	8	9	24	37	63	88	95	96	96
30	11	11	9	8	7	8	24	32	74	94	96	96	96

Average percent time operable = 39 percent.

Table 6. Gun Fire Mission longcrested percent time limited by various motions.

(a) Gun located at station 3.3.

GIUK Gap	Baseline	Optimized
Roll	13	2
Pitch	0	0
Wetness	0	0
Slams	0	0
Vert. Velocity	56	60
Total PTO	31	39

Open N. Atl.	Baseline	Optimized
Roll	15	0
Pitch	0	0
Wetness	0	0
Slams	0	0
Vert. Velocity	60	67
Total PTO	24	31

(b) Gun located at station 12.

GIUK Gap	Baseline	Optimized
Roll	23	5
Pitch	2	0
Wetness	0	0
Slams	0	0
Vert. Velocity	28	29
Total PTO	48	65

Open N. Atl.	Baseline	Optimized
Roll	26	6
Pitch	3	1
Wetness	0	0
Slams	0	0
Vert. Velocity	32	35
Total PTO	39	58

(c) Gun located at station 19.

GIUK Gap	Baseline	Optimized
Roll	15	2
Pitch	0	0
Wetness	0	0
Slams	0	0
Vert. Velocity	51	57
Total PTO	34	41

Open N. Atl.	Baseline	Optimized
Roll	17	2
Pitch	1	0
Wetness	0	0
Slams	0	0
Vert. Velocity	57	65
Total PTO	26	32

Table 7. Limiting criteria and longcrested PTO by speed and heading for optimized Underway Replenishment hull form at GIUK Gap, station 5.

(a) Limiting criteria.

Speed	Ship Heading Angle (deg)												
	Head						Beam						Following
(kn)	180	165	150	135	120	105	90	75	60	45	30	15	0
0	P	P	R	R	R	R	R	R	R	R	R	P	P
5	P	P	R	R	R	R	R	R	R	R	R	P	P
10	P	P	P	R	R	R	R	R	R	R	R	P	P
15	P	P	P	R	R	R	R	R	R	R	P	P	P
20	P	P	P	P	R	LFE	LFE	R	R	R	P	P	P
25	P	P	P	P	P	LFE	LFE	R	R	R	P	P	P
30	P	P	P	P	A	LFE	LFE	R	R	P	P	P	P

P = Pitch; R = Roll; A = Vertical Acceleration;
LFE = Lateral Force Estimator.

(b) Percent time operable.

Speed	Ship Heading Angle (deg)												
	Head						Beam						Following
(kn)	180	165	150	135	120	105	90	75	60	45	30	15	0
0	70	70	46	25	18	18	19	18	18	26	47	75	75
5	67	67	57	36	27	25	23	19	20	32	71	77	78
10	64	64	63	48	36	32	27	19	20	37	64	79	80
15	62	61	61	56	47	38	30	19	18	45	81	81	81
20	60	60	59	59	54	44	33	17	18	64	83	83	83
25	59	58	58	58	60	48	36	14	26	76	84	84	84
30	58	58	57	57	61	52	38	10	36	86	84	83	83

Average percent time operable = 49 percent.

Table 8. Underway Replenishment longcrested percent time limited by various motions.

(a) UNREP station located at station 5.

GIUK Gap	Baseline	Optimized
Roll	46	35
Pitch	18	13
Wetness	0	0
Slams	0	0
Vert. Accel.	1	0
LFE	2	3
Total PTO	33	49

Open N. Atl.	Baseline	Optimized
Roll	50	39
Pitch	22	17
Wetness	0	0
Slams	0	0
Vert. Accel.	1	0
LFE	2	3
Total PTO	25	40

(b) UNREP station located at station 10 or 15.

GIUK Gap	Baseline	Optimized
Roll	47	36
Pitch	19	13
Wetness	0	0
Slams	0	0
Vert. Accel.	0	0
LFE	1	3
Total PTO	33	49

Open N. Atl.	Baseline	Optimized
Roll	51	41
Pitch	23	17
Wetness	0	0
Slams	0	0
Vert. Accel.	0	0
LFE	1	3
Total PTO	25	40

Table 9. Percent time limited by criteria for baseline and optimized Underway Replenishment hull forms with and without appendages.

(a) Unweighted longcrested PTO at GIUK Gap.

	Bare Hull		With Appendages	
	Baseline	UNREP	Baseline	UNREP
Roll	65	64	46	35
Pitch	11	6	18	13
Vert. Accel.	0	0	1	0
LFE	0	0	2	3
Total PTO	24	30	33	49

(b) Unweighted longcrested PTO at open ocean North Atlantic.

	Bare Hull		With Appendages	
	Baseline	UNREP	Baseline	UNREP
Roll	67	67	50	39
Pitch	13	8	22	17
Vert. Accel.	0	0	1	0
LFE	0	0	2	3
Total PTO	20	25	25	40

Table 10. Percent Time Operable for ships and other missions.

(a) Unweighted longcrested PTO at GIUK Gap.

Ship	Towed Array	Gun Fire sta. 3.3	UNREP sta. 5	Average
Gun	69	39	51	53.0
Array	69	36	46	50.3
UNREP	67	38	49	51.3
Baseline	52	31	33	38.6

(b) Unweighted longcrested PTO at open ocean North Atlantic.

Ship	Towed Array	Gun Fire sta. 3.3	UNREP sta. 5	Average
Gun	58	31	42	43.6
Array	59	29	37	41.6
UNREP	57	31	40	42.6
Baseline	42	24	25	30.3

REFERENCES

1. Walden, D. A., P. J. Kopp, and P. Grundman, "Optimization of Hull Form for Seakeeping and Resistance," In: *Workshop in Developments in Hull Form Design.* Vol. 2 (1985).

2. Meyers, W. G., T. R. Applebee, and A. E. Baitis, "User's Manual for the Standard Ship Motion Program, SMP," DTNSRDC/SPD-0936-01 (Sep 1981).

3. Meyers, W. G. and A.E. Baitis, "SMP84: Improvements to Capability and Prediction Accuracy of the Standard Ship Motion Program SMP81," DTNSRDC/SPD-0936-04 (Sep 1985).

4. Kennell, C. G., B. L. White, and E. N. Comstock, "Innovative Naval Designs for North Atlantic Operations," In: *Trans. SNAME*, Vol. 93 (1985).

5. Smith, T. C. and W. L. Thomas III, "A Survey and Comparison of Criteria for Naval Missions," DTRC/SHD-1312-01 (Oct 1989).

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